

Appendix

I

# Sand Filter Design Example



## I.1 Sand Filter Design Example

### Data Required:

- Storm frequency = 15 years
- Storm duration = 24 hours
- Time of concentration =  $T_c = 5$  minutes
- From District of Columbia rainfall intensity - duration - frequency curve:  
intensity =  $i = 7.56$  inches/hour  
rainfall depth =  $d = 0.63$  inches

### Assumptions:

- The site is a parking lot with area =  $A = 10,000$  ft<sup>2</sup>
- The sand filter will outfall to a storm sewer.
- The distance is 50 feet from the sand filter's invert-out to the storm sewer pipe connection
- The invert of the city storm sewer = 92 feet at the proposed connection point (note: allow a 2% slope in the pipe connecting the invert-out of the sand filter to the city storm sewer invert)
- The runoff coefficient =  $c = 1.0$  (assuming 100% impervious surface)
- The first flush of runoff, or runoff depth to be treated =  $R = 0.5$  inches

### 1. Determine Design Invert Elevations

Determine the final surface elevation, invert in, invert out and bottom invert elevation of the structure.

- Invert in = 98 ft
- Invert out = 93 ft (beginning approximation)

Note: Actual head difference available within the filter between invert-in and invert-out is  
 $98 \text{ ft} - 93 \text{ ft} = 5 \text{ ft}$

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- Assume inflow pipe diameter = 1 ft
- Assume over the crown pipe cover = 2 ft
- Final surface elevation above sand filter = 101 ft = 98 ft + 2 ft + 1 ft
- Depth of filter layer:  $d_{f-max} = 3$  feet  
 $d_{f-min} = 1.8$  feet

### 2. Peak Discharge Calculation for Bypass Flow

The District of Columbia uses the 15-year storm (with  $t_c = 5$  minutes) for post-development runoff.

Using the Rational Method:

$$Q_{p15} = CIA$$

Where:

$Q_{p15}$	=	bypass peak flow (cfs)
$C$	=	runoff coefficient = 1.0
$I$	=	rainfall intensity = 7.56 in/hr
$A$	=	drainage area = 0.23 acres
$T_c$	=	time of concentration (used in selecting rainfall intensity)
	=	5 min

$$Q_{p15} = (1.0) (7.56 \text{ in/hr}) (0.23 \text{ ac}) = \underline{1.74 \text{ cfs}}$$

### 3. Determine Sand Filter Area $A_f$

Use the following equation:

$$A_f = 50 + (I_a - 0.1 \text{ ac}) * (167 \text{ ft}^2 / \text{ac})$$

Where:

$A_f$	=	surface area of filter layer (second chamber) ( $\text{ft}^2$ )
$I_a$	=	impervious area = 0.23 ac

$$A_f = 50 + (0.23 \text{ ac} - 0.1 \text{ ac}) (167 \text{ ft}^2/\text{ac}) = 71.2 \text{ ft}^2$$

$$\text{Use } A_f = \underline{80 \text{ ft}^2}$$

#### 4. Determine Storage Volume Needed

First, determine the water quality volume that must be treated in the sand filter using the following equation:

$$V_w = \frac{R * I_a}{12}$$

Where:  $V_w$  = water quality volume (ft<sup>3</sup>)  
 $R$  = runoff depth = 0.5 in for parking lots  
 $I_a$  = impervious area (ft<sup>2</sup>) = 10,000 ft<sup>2</sup>  
12 = conversion factor

$$V_w = \frac{0.5 \text{ in} * 10,000 \text{ ft}^2}{12} = \underline{416.7 \text{ ft}^3}$$

Calculate the volume of storage ( $V_s$ ) needed to accommodate the first flush of runoff from the parking lot using the following equation:

$$V_s = V_w - (F * T * A_f)$$

Where:  $V_s$  = storage volume needed to hold the first flush runoff (ft<sup>3</sup>)  
 $V_w$  = water quality volume = 416.7 ft<sup>3</sup>  
 $F$  = infiltration rate for sand  $\approx$  1.18 ft/hr  
 $T$  = filtering time = 1 hour based on NRCS practice  
 $A_f$  = surface area of filter layer (second chamber) = 80 ft<sup>2</sup>

$$V_s = 416.7 \text{ ft}^3 - (1.18 \text{ ft/hr}) (1 \text{ hr}) (80 \text{ ft}^2) = \underline{322.3 \text{ ft}^3}$$

**5. Calculate Submerged Storage Volume in Second Chamber**

$$V_{2b} = A_f * d_f * n$$

Where:  $V_{2b}$  = submerged volume of filter chamber (ft<sup>3</sup>)  
 $A_f$  = surface area of filter layer (second chamber) = 80 ft<sup>2</sup>  
 $d_f$  = depth of filter layer = 3 ft  
 $n$  = composite of porosity for filter media, for sand + gravel + perforated pipe = 0.6

$$V_{2b} = (80 \text{ ft}^2) (3 \text{ ft}) (0.6) = \underline{144 \text{ ft}^3}$$

**6. Calculate Submerged Storage Volume in First Chamber**

$$V_{1b} = A_1 * d_f$$

Where:  $V_{1b}$  = submerged volume of first chamber (ft<sup>3</sup>)  
 $A_1$  = surface area of first chamber (ft<sup>2</sup>)  
 $d_f$  = depth of filter layer (ft)

$$V_{1b} = (25 \text{ ft}^2) (3 \text{ ft}) = \underline{75 \text{ ft}^3}$$

**7. Calculate Surface Storage Volume in First & Second Chambers**

$$(V_{1t} + V_{2t}) = V_s - (V_{2b} + V_{1b})$$

Where:  $V_{1t} + V_{2t}$  = sum of surface volume of first & second chambers (ft<sup>3</sup>)  
 $V_s$  = storage volume needed to hold the first flush runoff (ft<sup>3</sup>)  
 $V_{1b}$  = submerged volume of first chamber (ft<sup>3</sup>)  
 $V_{2b}$  = submerged volume of filter chamber (ft<sup>3</sup>)

$$(V_{1t} + V_{2t}) = 322.3 \text{ ft}^3 - (144 \text{ ft}^3 + 75 \text{ ft}^3) = \underline{103.3 \text{ ft}^3}$$

**8. Determine H, Height Difference Available Between Top of Filter Layer and Bypass Pipe Outlet Invert**

$$V_{1t} + V_{2t} = (A_1 * H) + (A_f * H)$$

Where:  $V_{1t} + V_{2t}$  = sum of surface volume of first & second chambers (ft<sup>3</sup>)  
 $A_1$  = surface area of first chamber (ft<sup>2</sup>)  
 $A_f$  = surface area of filter layer (second chamber) = 80 ft<sup>2</sup>  
 $H$  = vertical distance between top of filter layer and bypass pipe outlet invert

Therefore:

$$H = \frac{(V_{1t} + V_{2t})}{(A_1 + A_f)} = \frac{103.3 \text{ ft}^3}{(25 \text{ ft}^2 + 80 \text{ ft}^2)} = 0.98 \text{ ft}$$

Use  $H = \underline{1 \text{ ft}}$

**8. Determine Maximum Storage Depth**

$$D = H + d$$

Where:  $D$  = maximum storage depth (ft)  
 $H$  = vertical distance between top of filter layer and bypass pipe outlet invert = 1 ft  
 $d$  = depth of filter layer (ft) = 3 ft

Note:  $D$  must be equal to or smaller than the difference between the invert in and invert out (5 ft)

$$D = 1 \text{ ft} + 3 \text{ ft} = 4 \text{ ft} \leq 5 \text{ ft (good)}$$

Use  $D = \underline{5 \text{ ft}}$

### 8.5 Determine Design Invert Out:

$$\text{design invert out} = \text{invert in} - D$$

$$\begin{aligned}\text{Where: } \text{invert in} &= 93 \text{ ft} \\ D &= \text{maximum storage depth} = 5 \text{ ft}\end{aligned}$$

$$\text{design invert out} = 98 \text{ ft} - 5 \text{ ft}$$

$$\text{design invert out} = \underline{93 \text{ ft}} \geq 93 \text{ ft (good, invert out approximated in Step 1} = 93 \text{ ft)}$$

Note: As first approximated in step 1, invert of outlet pipe is at 93 ft elevation. This elevation is higher than the public storm sewer (at 92 ft, see Step 1) at connection point and provides 1 ft (93 ft - 92 ft = 1 ft) of vertical elevation to accommodate the 2% slope requirement.

In this example, the connection to the storm sewer is 50 ft away from the invert-out of the sand filter. Therefore: 1 ft / 50 ft = 0.02 or 2% slope.

### 9. Determine Size of Bypass Pipe

Determine the capacity of the bypass pipe:

$$D = \left[ \frac{2.16 * n * Q_{p15}}{\sqrt{S}} \right]^{0.375}$$

$$\begin{aligned}\text{Where: } D &= \text{estimated bypass pipe diameter (ft)} \\ n &= \text{Manning's roughness coefficient} = 0.011 \\ Q_{p15} &= \text{bypass peak flow (cfs)} = 1.74 \text{ cfs} \\ S &= \text{pipe slope} = \text{assume } 0.5\% = 0.005\end{aligned}$$

$$D = \left[ \frac{2.16 * 0.011 * 1.74}{\sqrt{0.005}} \right]^{0.375} = 0.82 \text{ ft}$$

$$\text{Use } D = \underline{1 \text{ ft (12")}}$$



### 10. Determine submerged weir opening in first chamber

Since the weir opening in the first chamber is submerged, the orifice equation is used to calculate the dimensions of the weir opening:

$$Q_{p15} = C * A_{w1} * \sqrt{2gh_{\max}}$$

Therefore:

$$A_{w1} = \frac{Q_{p15}}{C * (2gh_{\max})^{0.5}}$$

Where:

$A_{w1}$	=	area of weir opening in first chamber (ft <sup>2</sup> ) = $h_{w1} * l_{w1}$
$h_{w1}$	=	weir height, assume 1 ft
$l_{w1}$	=	weir length (ft)
$Q_{p15}$	=	bypass peak flow (cfs) = 1.74 cfs
$C$	=	0.6
$g$	=	32.2 ft/sec <sup>2</sup>
$h_{\max}$	=	hydraulic head above the center line of weir (ft)
	=	[(invert in - invert out) - (h/2)]
	=	[(98 ft - 94 ft) - 1/2] = 3.5 ft

$$A_{w1} = \frac{1.74 \text{ cfs}}{0.6 * (2 * 32.2 \text{ ft/sec}^2 * 3.5 \text{ ft})^{0.5}} = 0.193 \text{ ft}^2 = h_{w1} * l_{w1}$$

Therefore:

$$l_{w1} = \frac{A_{w1}}{h_{w1}} = \frac{0.193 \text{ ft}^2}{1 \text{ ft}} = 0.193 \text{ ft} \quad (\text{minimum requirement})$$

Note: Assume 50% of the weir opening is clogged; therefore, use the following

$$l_{w1} = 2 \left( \frac{A_{w1}}{h_{w1}} \right) = 2 \left( \frac{0.193 \text{ ft}^2}{1 \text{ ft}} \right) = 0.386 \text{ ft}$$

Use  $l_{w1} = \underline{1 \text{ ft}}$

### 11. Structure dimensions (internal only):

Second Chamber:

$$A_f = L_2 * W$$

Where:  $A_f$  = surface area of filter layer (second chamber) = 80 ft<sup>2</sup>  
 $L_2$  = length of filter layer (second chamber) (ft)  
 $W$  = width of chamber, use 6 ft

Therefore:

$$L_2 = \frac{A_f}{W} = \frac{80 \text{ ft}^2}{6 \text{ ft}} = 13.3 \text{ ft}$$

Use  $L_2 = \underline{13.5 \text{ ft}}$

First Chamber:

$$A_1 = L_1 * W$$

Where:  $A_1$  = surface area of first chamber = 25 ft<sup>2</sup>  
 $L_1$  = length of first chamber (ft)  
 $W$  = width of chamber, use 6 ft

Therefore:

$$L_1 = \frac{A_1}{W} = \frac{25 \text{ ft}^2}{6 \text{ ft}} = 4.16 \text{ ft}$$

Use  $L_1 = \underline{4.5 \text{ ft}}$

Third Chamber:

Select  $L_3$  = length of third chamber = 3 ft

Therefore:

Length of structure,  $L = L_1 + L_2 + L_3 = 4.5 \text{ ft} + 13.5 \text{ ft} + 3 \text{ ft} = \underline{21 \text{ ft}}$

**11.5 Note: To prevent “short circuiting” in the filter chamber,**

$$L_1 + L_2 \geq 3 * W$$

$$4.5 \text{ ft} + 13.5 \text{ ft} \geq 3 \text{ ft} * 6 \text{ ft}$$

$$18 \text{ ft} \geq 18 \text{ ft (good)}$$

Total inner height inside sand filter:

$$D_t = D + \text{inflow pipe diameter} + \text{free board}$$

$$D_t = 5 \text{ ft} + 1 \text{ ft} + 2 \text{ ft} = \underline{8 \text{ ft}}$$

**12. Determine Flow Through Filter and Detention Time After Storage Volume Fills Up**

To determine the average flow through the filter, use:

$$q_f = k * A_f * i = k * A_f * \frac{h_{\max}}{2 * d_f}$$

Where:

$q_f$	=	average flow through the filter (ft <sup>3</sup> /hr)
$k$	=	sand permeability (ft/hr) = 0.6 ft/hr for mixed sand
$A_f$	=	surface area of filter layer (ft <sup>2</sup> ) = 80 ft <sup>2</sup>
$i$	=	hydraulic gradient (ft/ft)
$d_f$	=	thickness of the sand layer = 18 inches
$h_{\max}$	=	[(d + H) - (perforated pipe diameter / 2)]
	=	[(3 ft + 1 ft) - (6 in / 2) (1 ft / 12 in)] = 3.75 ft

Note: For accurate hydraulic computation, assume there are 6" diameter PVC perforated pipes at the bottom of the sand filter.

$$q_f = (0.6 \text{ ft/hr}) * (80 \text{ ft}^2) * [3.75 \text{ ft} / (2 * 1.5 \text{ ft})] = \underline{60.0 \text{ ft}^3/\text{hr}} = 0.016 \text{ cfs} \approx \underline{0.02 \text{ cfs}}$$

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To estimate the detention time, use:

$$T_s = \frac{V_s}{q_f}$$

Where:  $T_s$  = average dewatering time for sand filter (hr)  
 $V_s$  = storage volume needed (ft<sup>3</sup>) = 322.3 ft<sup>3</sup>  
 $q_f$  = average flow through the filter (ft<sup>3</sup>/hr) = 60.0 ft<sup>3</sup>/hr

$$T_s = (322.3 \text{ ft}^3) / (60.0 \text{ ft}^3/\text{hr}) = \underline{5.4 \text{ hrs}} \leq 72 \text{ hrs (good)}$$

### 11. Develop Inflow and Outflow Hydrographs

A. Inflow hydrograph data:

- area = 10,000 ft<sup>2</sup> = 0.23 ac
- frequency = 15 yr
- duration = 24 hr
- time of concentration,  $T_c$  = 5 min
- runoff coefficient,  $C$  = 1.0

Rational Method:  $Q = CIA = 1.0 * I * 0.23 \text{ ac}$

T (min)	I (in / hr)	Q (cfs)
0	0	0
5	7.56	1.74
10	6.30	1.45
15	5.44	1.25
20	4.82	1.11
30	3.95	0.91
45	3.16	0.73
60	2.66	0.61

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B. Time at which outflow hydrograph begins (choose 1):

When:  $t_c * Q_p < 2V_s$  Then

$$T = 2t_c - \left( 2t_c^2 - \frac{2V_s * t_c}{Q_p} \right)^{0.5}$$

When:  $t_c * Q_p = 2V_s$  Then

$$T = 0.5t_c + \left( \frac{V_s}{Q_p} \right)$$

When:  $t_c * Q_p > 2V_s$  Then

$$T = \left[ \frac{2V_s * t_c}{Q_p} \right]^{0.5}$$

Note:  $T_c * Q_p \text{ } \underline{\hspace{1cm}} \text{ } ? \text{ } 2 * V_w$

$(5 \text{ min}) * (1.74 \text{ cfs}) \text{ } \underline{\hspace{1cm}} \text{ } ? \text{ } 2 * (322.3 \text{ ft}^3)$

$522 \text{ ft}^3 < 645 \text{ ft}^3$

Note: Since the inequality fits #1 above, use the appropriate equation to solve for T.

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When:  $t_c * Q_p < 2V_s$  Then

$$t_p = 2t_c - \left( 2t_c^2 - \frac{2V_s * t_c}{Q_p} \right)^{0.5}$$

$$t_p = 2 * 5 \text{ min} - \left( 2 (5 \text{ min})^2 - \frac{2 (322.3 \text{ ft}^3) (5 \text{ min})}{1.74 \text{ cfs}} \right)^{0.5} = \underline{5.6 \text{ min}}$$

Note: At a filling time,  $T = 5.6 \text{ min}$ , the flow or  $Q \approx 0.02 \text{ cfs}$